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New results on the incipient separation of shock/boundary-layer interactions

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Abstract

Incipient separation of shock/boundary-layer interactions (SBLIs) is reexamined through RANS simulations of the turbulent flow past a sharp-edged ramp at Mach 3. Surprisingly, it was found that separation occurs for ramp angles below the accepted incipient value and for extremely small ramp angles. However, the separation bubble is very much smaller for ramp angles below incipient, which can still be regarded as a demarcation between "small-" and "large-scale" separation. Further study is recommended.

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Keywords: Shock; boundary layer; flow separation

1. Introduction

Shock/boundary-layer interactions (SBLIs), particularly turbulent ones, are pervasive problems of high-speed aerodynamics. They are difficult to prevent and the possibility that the interaction is separated is high. Thus, solution strategies generally revolve around attempts to reduce the separation zones. A critical fundamental issue of shock-induced separation is its onset, also known as incipient separation. Theoretically, for a two-dimensional flow, incipient separation is defined where the surface shear stress vanishes. Such a definition is exact for a laminar flow but may be interpreted as a time-averaged location if the flow is turbulent.

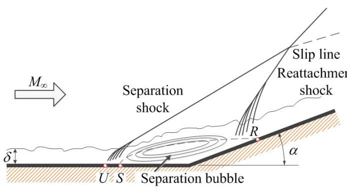

Fig. 1. Schematic of a ramp-induced, separated SBLI.

Specifically, consider the separated flow induced by a ramp inclined at an angle of α to the freestream, as shown schematically in Fig. 1. The most upstream location of the interaction is known as the upstream influence and is denoted by U, the boundary layer separating at S and reattaching at R. The skin friction coefficient at these points

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vanish and negative values exist between them. At incipient separation, S and R collapse into a single point. In practice, the definition of boundary-layer separation (or reattachment) based on vanishing skin friction is difficult to implement—" a very delicate task" for SBLIs according to [1]. Various approaches were proposed and only two are highlighted here. The first strikes a tangent of the maximum slope in the surface pressure rise. The intersection of this tangent with the surface locates S [2]. The second makes use of surface oil flow visualization [3]. In this technique, a layer of oil carrying a pigment is applied in front of the interaction region. During a run, the oil spreads downstream but does not travel past the separation zone. Careful measurements indicate that the surface oil flow visualization and the maximum tangent in the initial pressure rise yield essentially identical separation points.

An aspect of fundamental interest is incipient separation. Elfstrom [4] compiled incipient separation data, subsequently enlarged, for SBLI induced by a sharp ramp at the incipient angle α_I, as shown in Fig. 2. The figure includes three data points, highlighted by a circle and which will be discussed later. The data show a strong dependence of α_I on Mach number in the supersonic range, trending toward Mach independence in the hypersonic range.

Settles et al. [3] observed that incipient separation does not occur abruptly but gradually. This can be interpreted to imply that separation exists for ramp angles less than α_I, which we will call "sub-incipient separation." This observation has not been well studied or understood. If incipient separation does not occur per Elfstrom's compilation and criteria in [1] then further understanding of the self-induced, free interaction process is needed. The objective of this study is to provide preliminary observations of the incipient separation of SBLI using two-dimensional simulations.

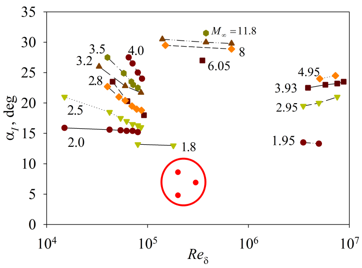


Fig. 2. Incipient separation, adapted from [4].

2. Method

2.1. Numerical approach

The NASA FUN3D code was used for the simulations with a k–ω SST turbulence model. FUN3D is a node-based, finite volume code that has advanced capabilities over speed regimes ranging from subsonic to hypersonic. The flux construction was accomplished using a hybrid approach which employs Van Leer construction near shocks and a low-diffusion flux-splitting scheme near walls. A stencil-based Van Albada flux limiter along with gradient-based h-refinement were used to ensure proper resolution of the discontinuities in the flowfield.

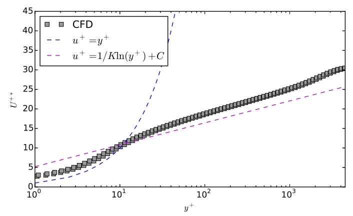


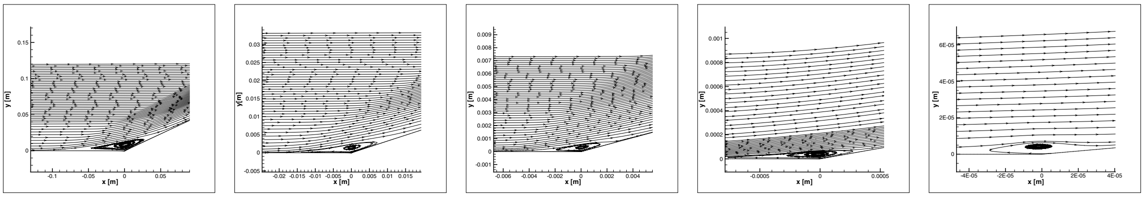
Fig. 3. Undisturbed boundary layer profile; $K = 4.1$, $C = 5.2$.

2.2. Test conditions

A fully turbulent boundary layer was developed on a flat plate at zero incidence to an incoming flow at Mach 3, a unit Reynolds number of 63 million/m, a wall temperature ratio of $T_w/T_o = 1.05$ which is close to adiabatic and a total pressure $p_o = 689$ kPa to closely match [3]. A ramp at an incidence angle of α was placed with its leading edge 1.5 m downstream of the leading edge of the flat plate. The turbulent boundary layer was fully developed at that location x_0 with the distinctive log-law and wake regions; see Fig. 3. The pertinent boundary-layer parameters are: $\delta_0 = 15.275$ mm, $\delta_0^* = 3.493$ mm, $\theta = 0.6639$ mm, $H = 5.26$, $\delta_i^* = 1.215$ mm, $\theta_i^* = 0.9788$ mm, $H_i = 1.24$, and $c_{f_0} = 0.001177$. Settles et al. [3] suggested $\alpha_I = 18$ deg, the value used in the present simulations. Simulations were performed at various α values above and below the incipient value.

3. Results and discussion

The streamline plots in Fig. 4 clearly show a massive separation zone for $\alpha = 25$, decreasing in size as the ramp angle decreases. Moreover, the figure shows a distinct separation region for angles below the accepted incipient ramp angle, even down to 5 deg. The 2.5 deg results with a very tiny separation region are not shown for brevity. The



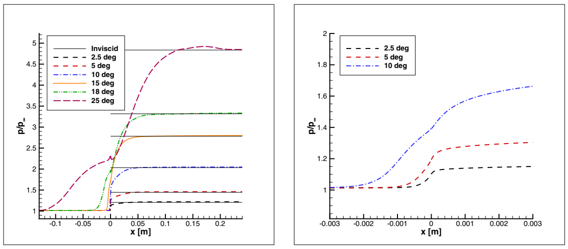
(a) α = 25 deg. (b) α = 18 deg. (c) α = 15 deg. (d) α = 10 deg. (e) α = 5 deg.

Fig. 4. Streamlines for turbulent interactions.

above results confirm Settles et al.'s [3] observation that separation is a gradual process and may exist at small ramp angles. The differences in the lengthscale between massive and subincipient separation are also evident in the surface pressure and skin friction distributions shown in Figs. 5 and 6 respectively. Thus, instead of vanishing, the present results show that the separation zone exists but is much smaller. In other words, the incipient separation criterion may be interpreted as a demarcation between largescale and smallscale separation.

Figure 5(a) shows that the surface pressure distributions for α = 25, 18 and 15 deg exhibit a distinctive kink ahead of the corner location that is indicative of separation [2]. However, this kink is also evident in the α = 10 deg case as shown in Fig. 5(b). It is thought that the kink is also present at lower ramp angles but could not be resolved by the present computations. The extent of the separation zone is also evident in the skin friction plots which reveal that there is a distinct length between the separation and reattachment points even at α = 2.5 deg.

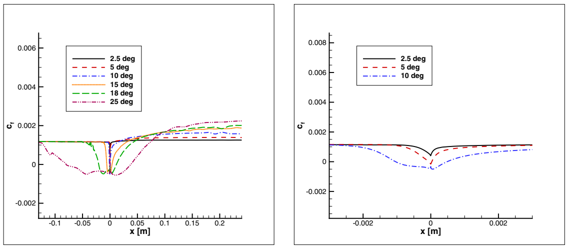
Based on the above evidence, it is also interesting to examine recent evidence of sub-incipient separation is provided from studies of micro-vortex generators (MVGs) [5]. These MVGs, one of which is shown schematically in Fig. 7(a), are pyramidal ramps with finite span whose height is less than the boundary-layer thickness so that their leading edges are at very shallow angles. Since the MVGs are not exposed to freestream conditions, their shallow leading-edge angle means that they should not cause separation. Experimental and computational studies, however, show the existence of a separation zone ahead of the MVG leading edge as can be seen in Fig. 7 where the freestream Mach number is 2.5. Based on Elfstrom's compilation, the ramp angle for incipient separation should be about 15 deg but the leading edge of these ramps are 8.9 deg. The cluster of encircled data in Fig. 2 represents MVG data from different sources [5,8,9], all showing evidence of sub-incipient separation. For the MVGs, the separation may be thought to be due to the exposure to an incoming flow at a much lower Mach number than the freestream. This is not an easy argument to make since shock detachment for a 8.9 deg ramp occurs at Mach 1.38. In other words, is separation of SBLIs, at least ramp-induced ones, ultimately due to a local transonic interaction?



(a) The distinctive kink in the pressure distribution for separated interactions.

(b) Close-up for α = 2.5, 5, 10 deg.

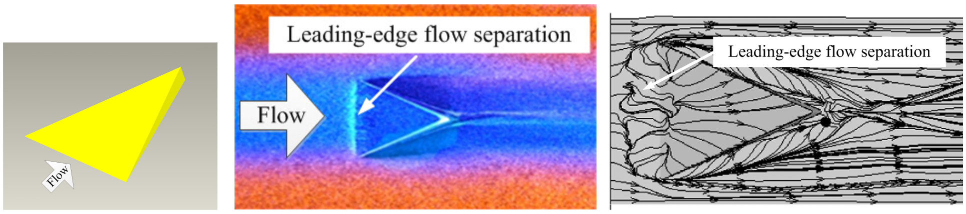
Fig. 5. Surface pressure distribution.



(a) Negative skin friction coefficients for all cases studied.

(b) Close-up for α = 2.5, 5, 10 deg.

Fig. 6. Skin friction distribution.



(a) MVG schematic.

(b) Surface flow visualization showing MVG leading-edge separation [6].

(c) Numerical surface topology showing MVG leading-edge separation [7].

Fig. 7. Evidence of separation due to micro-vortex generator.

4. Conclusions

A numerical study was performed to gain preliminary insight into an observation by Settles et al. [3] that separation in ramp-induced SBLI is a gradual process, with a distinct small separation zone when the ramp angle is below an incipient value but becomes large beyond that. It was thought that this sub-incipient separation may be similar to separation observed in micro-vortex generators. Further study is needed to properly understand of this phenomenon.

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